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Mini-Review

# Environmental consequences of ship-induced drawdown in shallow waterways

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## Abstract

Much attention has been devoted to detrimental impacts of shipping on coastal and inland infrastructure recently. Yet, transport over water remains several times more energy efficient than alternative transport modes and therefore plays a crucial role in global energy efficiency and decarbonisation strategies. Understanding and predicting these impacts is thus essential for developing effective mitigation strategies where necessary. Among the main phenomena causing damage to estuarine and other inland infrastructure is the so-called drawdown, a part of ship-generated primary wave system, representing a local depression of the water surface induced by vessel motion, particularly evident in shallow or confined waterways. This phenomenon alters nearshore hydrodynamics and sediment stability, and the associated return currents can also mobilise or erode bed morphology. Moreover, rapid water level depressions and subsequent surges pose safety hazards to recreational users and swimmers in nearshore zones. Understanding the environmental implications of drawdown is therefore critical for managing sediment dynamics, bank stability, and public safety in intensively navigated waterways. Exiting research on ship-induced drawdown is reviewed, integrating shallow and confined water ship hydrodynamics, ecological impacts, and mitigation strategies. The analysis highlights environmental effects associated with drawdown-induced sediment resuspension and shoreline erosion and identifies knowledge gaps in predictive modelling and ecosystem management.

**Key words:** Drawdown, environmental impact, inland navigation, inland waterways, shallow water, ship hydrodynamics, ship primary waves

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## Introduction

With the continued growth of international trade, the shipping industry has become increasingly prominent. Shipping is widely recognised as one of the most efficient and sustainable modes of cargo transportation in terms of safety, fuel consumption, and carbon emissions, which has made it a preferred option for the global trade of goods and products. Between 1990 and 2021, the volume of cargo transported by ships more than doubled, increasing from approximately 4 to nearly 11 billion tonnes (Statista 2026). However, the expansion of shipping lanes and the growth in cargo volumes have also given rise to a range of environmental challenges. In addition to direct impacts such as noise disturbance (Graham and Cooke 2008), vessel strikes on marine organisms (Pirotta et al. 2019), and

the release of chemical pollutants (Burgin and Hardiman 2011), including carbon oxides and heavy metals from antifouling paints (Dafforn et al. 2011; Adouane et al. 2026), ship-generated waves represent another non-negligible source of environmental impact (Gabel et al. 2017). Previous studies have shown that ship-generated waves and currents can lead to sediment resuspension and shoreline erosion, ultimately causing alterations in bottom morphology, and influencing bank stability (Göransson et al. 2014; Gabel et al. 2017; Ulm et al. 2020; Chakraborty et al. 2022). Ship-generated waves may also pose safety risks to swimmers and other recreational water users. Survey results from lakes in Ontario indicate that swimmers are frequently destabilized by waves from passing vessel (Houser et al. 2024). De Jong et al. (2013) reported a fatal incident in the Port of Rotterdam where a steep wave generated by a passing container vessel swept anglers from the shoreline into the water. Canals and estuaries function as critical transit corridors for inland goods transportation, linking maritime trade with inland ports, and consequently are very sensitive to increases in shipping traffic.

Among the various components of ship-generated hydrodynamics, ship-induced drawdown, which forms part of long-period primary wave system, has been identified as a particularly influential mechanism in shallow and confined waterways (Dempwolff et al. 2022). As a ship moves through water, it alters the surrounding pressure and velocity fields. Water from the bow is redistributed toward the stern, generating a return current opposite to the direction of ship motion. According to Bernoulli's principle, increased flow velocity along the sides of the hull leads to a reduction in pressure, while stagnation points near the bow and stern result in locally elevated pressure and water levels. This pressure distribution causes a depression of the free surface along both sides of the hull, commonly known as drawdown wave, as illustrated in Fig. 1. Bertram (2012) demonstrated that lateral confinement and depth limitations in shallow channels can intensify flow velocities alongside a vessel by reducing the available flow area, thereby amplifying the resulting drawdown wave. Additionally, the increasing use of canals has made long-period drawdown waves more frequently observed, and the energy they carry has raised growing concerns among regulators and researchers seeking to protect the environment.

To address these issues, this review aims to synthesise current knowledge on the environmental consequences of ship-induced drawdown in shallow and confined waterways. Specifically, this review aims to: (1) summarise the hydrodynamic mechanisms governing drawdown generation and propagation in inland navigation channels, (2) Evaluate the ecological and geomorphological impacts associated with drawdown-induced sediment resuspension, shoreline erosion, and habitat disturbance, and (3) Review existing mitigation and management approaches and identify research gaps for improving predictive modelling and environmental management of intensively navigated waterways.

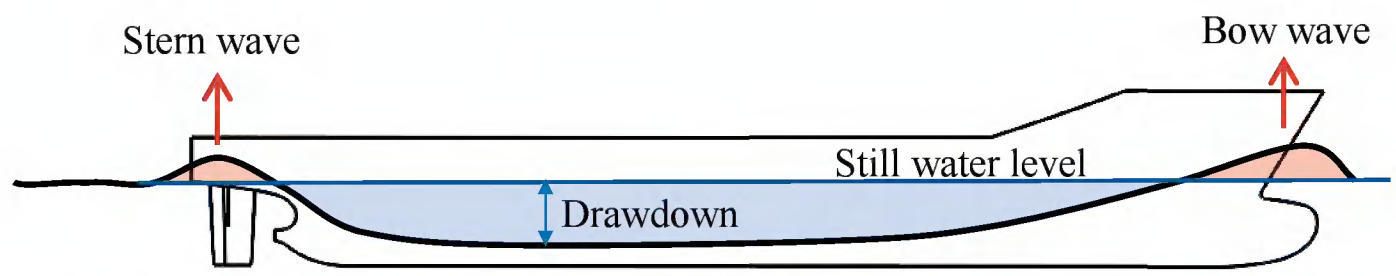


**Figure 1.** Lateral view of the ship-generated primary wave system (redrawn after Dempwolff et al. 2022).

## Aspects and evidence of ecological disturbance

### Hydrodynamics

In contrast to transoceanic shipping lanes, canals and other inland waterways are characterised by confined hydrodynamic conditions, making near-bed and riparian ecosystems more easily disturbed by ship-induced waves. To quantify the degree of confinement, researchers proposed the blockage ratio ($m$), defined as:

$$m = \frac{A_S}{A_C} \tag{1}$$

in which $A_S$ and $A_C$ are the cross-sectional area of the vessel and channel respectively. Together with the depth Froude number ($Fh$) introduced by Havelock (1908) (Eq. (2)), shallow-water navigation can be classified into three regimes with the critical blockage ratio ($m_{crit}$) curve in Eq. (3): subcritical, transcritical, and supercritical, as illustrated in Fig. 2 (Lataire et al. 2012).

$$Fh = \frac{V}{\sqrt{gh}} \tag{2}$$

$$m_{crit} = 1 - \sin\left(3\arcsin\left(\frac{Fh^{2/3}}{2}\right)\right) \tag{3}$$

in which $V$ is the vessel speed, $\sqrt{gh}$ is the wave speed, $g$ is the acceleration due to gravity, and $h$ represents the water depth of the canal. In the transcritical regime, hydrodynamic instabilities arise because the flow cannot pass steadily through the gap between the ship hull and the canal boundaries (Terziev et al. 2023). Previous studies have shown that vessels operating in the supercritical regime experience reduced resistance and may therefore achieve improved fuel efficiency (Li and Ellingsen 2016). However, for most cargo and container ships, the nonlinear behaviour of the force experienced by a vessel with higher

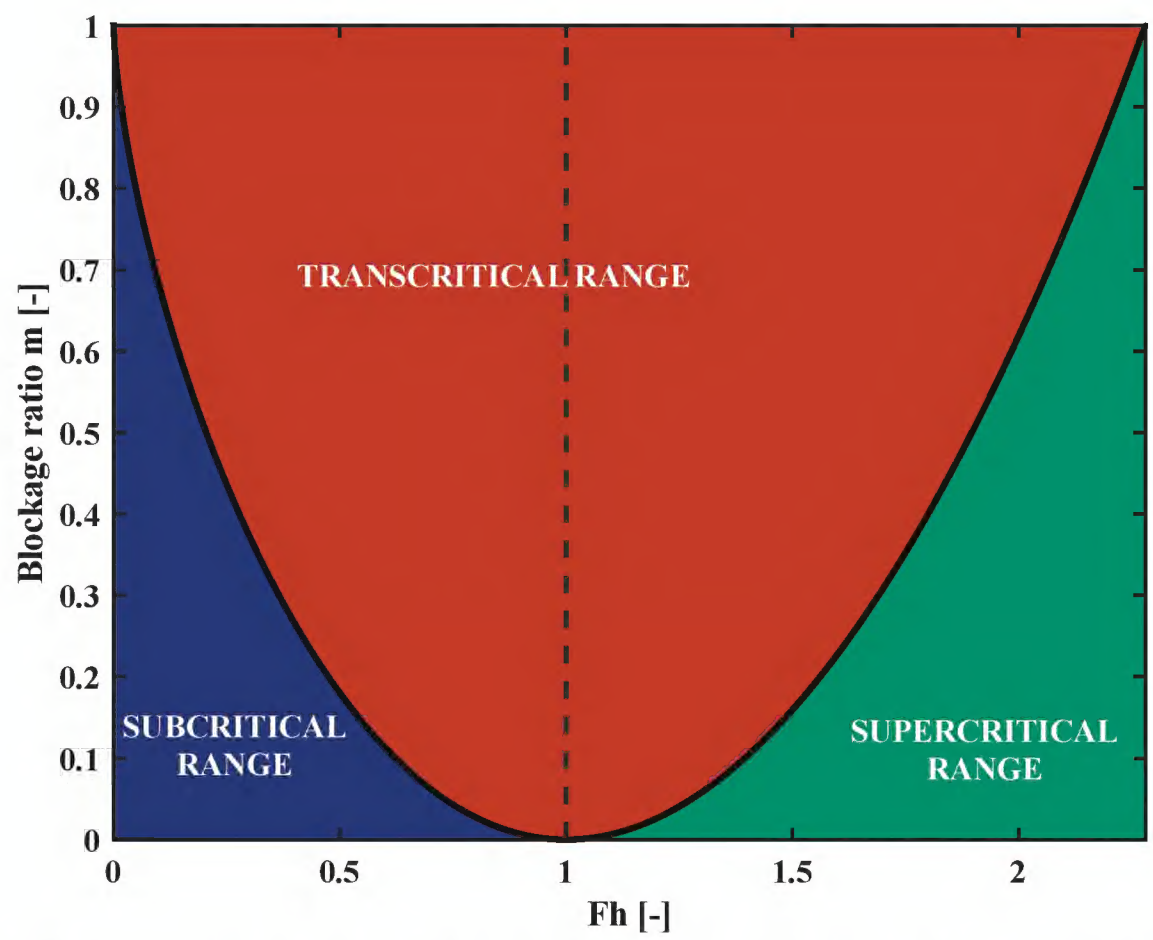


**Figure 2.** Regime classification of shallow-water navigation as a function of the depth Froude number and the blockage ratio (Lataire et al. 2012).

speed leads to an increase in the power required to overcome resistance in the transcritical regime, making sustained operation in the supercritical regime impractical (Terziev et al. 2018).

Hydrodynamic differences in shallow water enhance the prominence of drawdown in confined waterways, thereby enabling it to propagate over long distances away from the ship (Maynord 2004). In confined waterways, the presence of lateral boundaries restricts the spreading of ship-generated waves, causing wave energy to remain concentrated and propagate along the channel over long distances. By contrast, in open water, wave energy spreads laterally and therefore dissipates faster. This difference in energy propagation is also reflected in the variation of the Kelvin half-angle with depth Froude number, which governs the direction and extent of wave propagation in shallow and confined water conditions (Terziev et al. 2023). The hydrodynamic conditions described above form the physical basis for many of the sedimentary and ecological disturbances observed in intensively navigated inland canals and estuaries, which are discussed in the following section.

## Ecological impacts

Sediment resuspension caused by ship passages has been widely documented in rivers and navigation channels (Gabel et al. 2017; Duró et al. 2020). Unlike wind-generated waves, ship-induced waves exhibit distinct characteristics, including the ability to significantly enhance local current velocities and produce abrupt increases in hydraulic loadings (Rapaglia et al. 2015). Sediment resuspension and bank erosion are controlled by whether the hydrodynamic bed shear stress ($\tau$) induced by drawdown currents exceeds the critical shear stress ($\tau_c$) for incipient motion. Critical shear stress can be determined using a Shields equation (Shields 1936):

$$\tau_c = \Theta_c \left(\rho_s - \rho_f\right) g D_i \tag{4}$$

in which $\Theta_c$ is the dimensionless Shields coefficient, which depends on factors such as grain-size distribution, particle exposure, and channel geometry, and typically ranges from 0.02 to 0.08 for non-cohesive sediments (Schwendel et al. 2010). $\rho_s$ and $\rho_f$ represent the densities of sediment and fluid respectively while $D_i$ denotes the substratum grain size. Reported values of critical shear stress in inland waterways range from 0.001 Pa to 2 Pa (Zhao et al. 2022). In comparison, field measurements in the Grand Canal indicate that maximum ship-induced bed shear stresses range from approximately 4 Pa to over 8 Pa, depending on vessel type and wave characteristics (Mao and Chen 2020). Schoellhamer (1996) reported that sediment resuspension induced by long-period primary ship waves was of greater magnitude than that caused by wind-generated waves, based on field investigations conducted in Hillsborough Bay, USA. Field measurements in the Göta Älv River, Sweden, showed that maximum turbidity levels were primarily controlled by drawdown magnitude and could be predicted from parameterised bed shear stress, whereas secondary waves played a less significant role (Göransson et al. 2014). Several aquatic species are highly dependent on clear-water conditions, including charophytes and widgeon grass, which are particularly sensitive to increased turbidity, meaning that ship waves have biological impacts (Verhoeven 1979; Eriksson et al. 2004).

**Table 1.** Cumulative shoreline retreat in the study area along the Malamocco Marghera channel from 1974 to 2015 (Zaggia et al. 2017).

| Year | Progressive retreat (m) | Average retreat rate (m/year) |
|---|---|---|
| 1974 | 0 | N/A |
| 1978 | 1 | 0.26 |
| 1987 | 67 | 7.39 |
| 1994 | 76 | 1.29 |
| 2004 | 107 | 3.05 |
| 2005 | 108 | 1.16 |
| 2009 | 111 | 0.73 |
| 2010 | 118 | 6.14 |
| 2012 | 125 | 3.95 |
| 2014 | 130 | 2.81 |
| 2015 | 133 | 1.73 |

Beyond short-term resuspension, repeated ship passages contribute to sediment redistribution and longer-term morphological change. Resuspended material may be transported and redeposited in undesired locations, leading to alterations in bed morphology and sediment grain-size distributions (Zaggia et al. 2017). Clear evidence of such processes has been reported in confined navigation channels. In the Port of Marghera, Italy, the drawdown generated by large vessels has been observed to reach amplitudes of up to 2.45 m. As shown in Fig. 3, this substantial drawdown has resulted in the mobilisation of large sediment volumes and has been associated with coastline retreat rates of up to 4 m per year, demonstrating the potential for ship-induced hydrodynamics to drive significant long-term morphological change (Zaggia et al. 2017). Table 1 illustrates the shoreline retreat Geographic Information System (GIS) analysis data between 1974 to 2015 in this in-situ survey. Additionally, field measurements from a tidal shipping channel in the Savannah River, Georgia, indicate that long-term shoreline retreat rates reach approximately 1.39 m per year along the main channel shoreline and 0.35 m per year in the sheltered South Channel of Bird/Long Island (Muscalus and Haas 2022). In the Cho Gao Canal, Vietnam, heavy boat traffic exceeding 1500 vessels per day produces large waves that progressively erode the canal banks, resulting in 2–3 m of bank loss along both sides of the canal, while the most affected sections experience riverbank collapse of approximately 4 m per year (Anh and Thuy 2022).

Habitat loss of flora and fauna is another important threat caused by the drawdown waves (Liedermann et al. 2014). Beyond ship-induced sediment resuspension, which alters underwater light levels and shades the living conditions of aquatic flora, the primary wave system has also been shown to trigger nutrient release and biochemical changes through sediment disturbance and porewater exchange. Field observations indicate that ship motion may cause porewater pumping, thereby increasing ammonia levels in the water column. This process may enhance nutrient availability, contribute to eutrophication, and consequently negatively influence seagrass habitat (Koch 2002). Xue et al. (2021) reported that biogenic element ratios (e.g. Si/Ti and Br/Cl) in sediment cores collected from a shipping lane were reduced as a result of recurrent ship passages. As these elemental ratios are commonly used as evidence for bio-

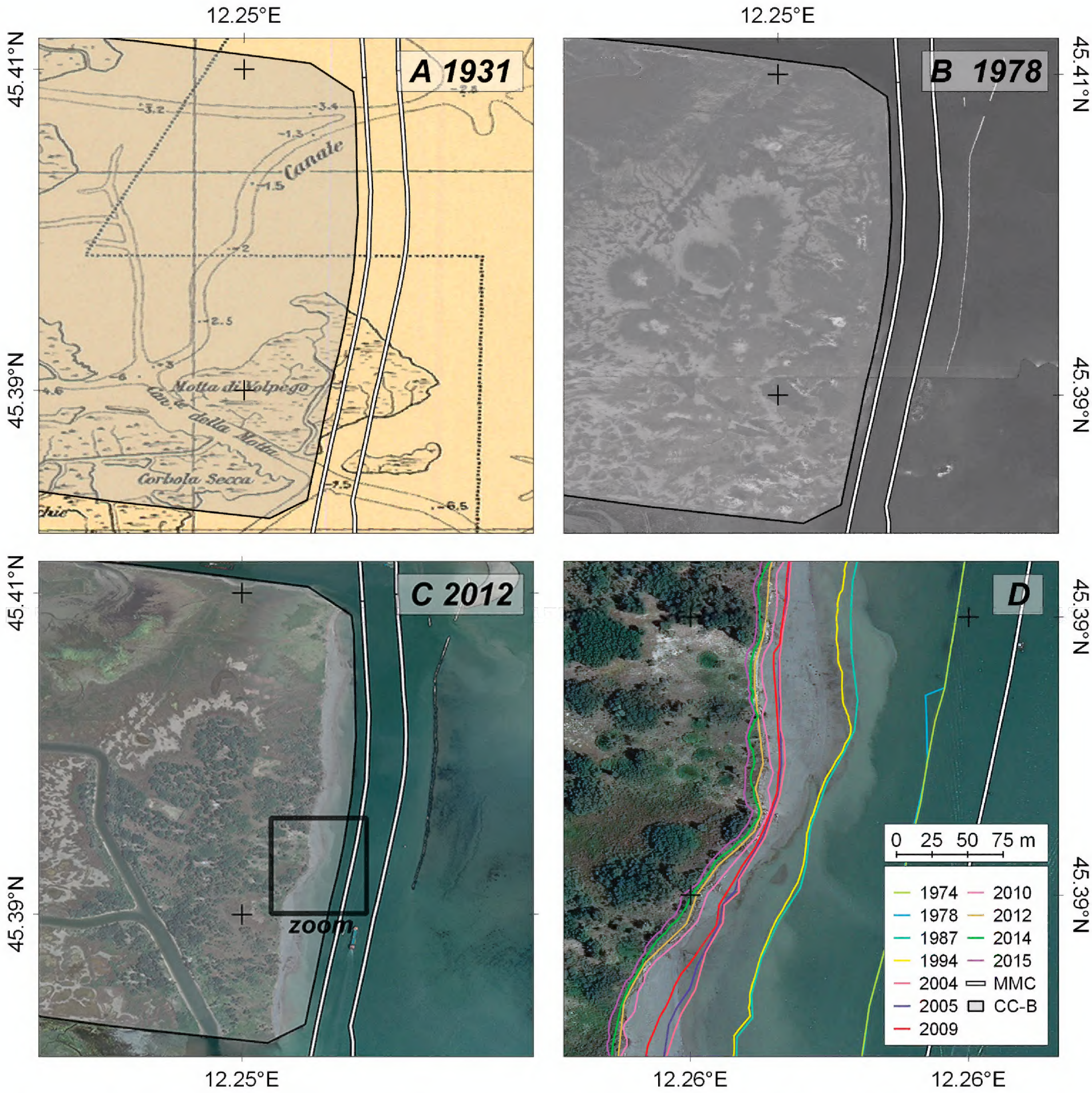


**Figure 3.** Shoreline evolution in the Port of Marghera between 1931 and 2015. Image **A**, **B** and **C** illustrate the shoreline changes from 1931 to 2012, while panel **D** presents a zoomed-in view of the study area showing shoreline positions for different years. The navigation channel margins are indicated by white lines (Zaggia et al. 2017).

logical productivity (Xue et al. 2021), their decline indicates that intensive shipping activity on the Zhejiang coast has likely led to a reduction in phytoplankton primary productivity in the region. More directly, mechanical damage caused by ship-generated waves can directly affect aquatic vegetation. In the River Nile, ship-induced waves have been reported to wash out floating plants, uprooting lightly anchored species and cause mechanical damage to more firmly rooted vegetation through drag forces and tearing (Ali et al. 1999).

In addition to effects on flora, vessel-induced hydrodynamics have been shown to directly affect aquatic fauna, especially during early life stages. Adams et al. (1999) found that ship-induced drawdown can strand young fishes (e.g. shovelnose sturgeons), as fishes may be washed ashore by return currents and

subsequently left exposed on the dry bank slope by the drawdown. Based on systematic experiments, Gabel et al. (2012) showed that a vessel navigating at a speed of 12 km/h (6.48 knots) can generate a near bed shear stress of up to 1 Pa via waves. Under such shear stress, 45% of littoral benthic invertebrates may be detached, potentially altering predator–prey interactions between fish and invertebrates and thereby affecting a key component of the aquatic food web. A more recent study by Flödl et al. (2025) focused on near-bed turbulence measurements at a gravel bar upstream of Vienna. Using near-bed flow velocity measurements over approximately one year of field monitoring, the study compared hydrodynamic conditions during natural flow and during ship passages to evaluate the influence of navigation on bed shear stress and turbulence affecting benthic habitats. On the other hand, as the vital habitats for juvenile fishes, estuaries are under pressure of increasing turbidity levels caused by intensive shipping events. Lowe et al. (2015) found that the turbidity level increase have negative effects on the health of fishes by impairing gill function, causing gill deformation, and increasing parasite loads. Numerous ecological disturbances associated with shipping have been reported. However, most studies describing these ecological consequences rely on qualitative observations, and quantitative assessments of biodiversity impacts remain limited (Jägerbrand et al. 2019). Overall, the evidence suggests that ship-induced drawdown functions as a source of physical disturbance and ecological stress, with cascading consequences for aquatic food webs.

## Mitigation and management approaches

Given the longstanding concern over shoreline geomorphological and ecological damage caused by ship-induced waves, numerous mitigation strategies have been developed and assessed to reduce these impacts. Firstly, introducing speed and traffic intensity regulations for navigation is a straightforward method as ship speed and blockage ratio is strongly correlated with the magnitude of primary ship waves (Dempwolff et al. 2022). However, speed restrictions may lead to longer transit times, thereby generating potential negative consequences for freight transport efficiency and shipping costs (Melling et al. 2025).

On the other hand, options for mitigating the impacts of ship wakes on shorelines include the use of coastal protection infrastructure, ranging from traditional hardened structures (e.g. groins and breakwaters) to nature-based solutions such as vegetated shorelines or oyster reefs, as well as hybrid approaches that integrate both strategies (Gabel et al. 2017). Intensive field measurements have shown that, although groins are constructed to modify near-bank hydrodynamics and mitigate shoreline erosion, they nevertheless experience structural damage due to increased loads induced by ship-generated waves (Mares-Nasarre et al. 2024). Ju et al., (2023) investigated two types of vertical dissipative revetments and found that they can effectively reduce ship-induced primary wave height by approximately 20–25%. However, the increased wave fluctuation generated by these structures may have non-negligible adverse effects on navigation safety. Nature-based management approaches offer multiple benefits for both erosion mitigation and ecosystem conservation. Almström et al. (2022) evaluated a hybrid shoreline protection solution combining a stone-based sill with vegetation. After 2.5 years of monitoring, the approach was

shown to effectively mitigate both ship-induced primary and secondary waves. Moreover, given that vegetation is a key component of nature-based solutions, the selection of appropriate plant species is crucial for the broader application of such approaches across different regions. In Samut Sakhon, Thailand, the rehabilitation of mangroves was considered an effective measure for reducing the erosion rate along highly eroded shorelines. However, the survival of mangrove strongly depended on local wave exposure (Naohiro et al. 2012). Long-term monitoring periods should also be carefully considered when evaluating the costs and benefits of the methods.

## Conclusion

Ship-induced loads in estuaries and inland waterways have raised growing concern worldwide. Understanding hydrodynamics within shipping lanes is a critical first step toward protecting shorelines and mitigating ship-induced damage to aquatic ecosystems. As outlined in this review, ship-generated primary wave systems (e.g. drawdown waves) carry substantial energy and can significantly alter near-bank hydrodynamics. Such disturbances promote sediment resuspension and redistribution, over longer timescales, can lead to persistent changes in canal bank morphology. Furthermore, abundant field evidence suggests that these physical disturbances propagate through aquatic ecosystems, affecting water transparency, nutrient dynamics, and habitat suitability for both flora and fauna. In addition, the navigation of large vessels introduces risks to shoreline users, including swimmers and moored vessels.

Given projections that inland shipping activity will increase significantly worldwide (Barros et al. 2022), and the speed regulations alone cannot fully resolve the aforementioned issues, a range of strategies has been proposed to mitigate or alleviate pressures on riparian ecosystems. The most widely adopted and straightforward approaches are hardened structures such as groins and revetments. However, the potential decline in effectiveness over time, together with the relatively high construction and maintenance costs of such approaches, also poses considerable challenges. Nature-based methods have become increasingly attractive in recent years, as they generally require lower maintenance costs and offer eco-friendly benefits, such as providing habitat for aquatic fauna and enhancing the stability of riparian soils. Nevertheless, the strong regional dependence of suitable plant species, together with the time required for such measures to become effective, limits the large-scale implementation of nature-based approaches.

The present review underlines the importance of considering ship-induced drawdown waves as a crucial factor in estuarine and inland waterways. Future research should focus on establishing standardized monitoring frameworks for ship-induced hydrodynamic disturbances in inland waterways. Long-term field measurements combined with high-resolution hydro-ecological modelling are needed to better quantify the links between ship-generated waves, sediment transport, and ecological responses. In addition, the development of threshold-based environmental regulations based on hydrodynamic indicators such as drawdown magnitude and bed shear stress may provide effective management protocols for navigated waterways. Finally, the interaction between ship-induced disturbances and climate change interactions (CCI) should be further

investigated to improve the resilience of inland waterway ecosystems under future climate conditions. At the same time, further research may explore the feasibility of harvesting energy from ship-induced hydrodynamic disturbances, which could potentially transform these impacts into a supplementary renewable energy resource while contributing to sustainable waterway management.

## Additional information

### Conflict of interest

The authors have declared that no competing interests exist.

### Ethical statement

No ethical statement was reported.

### Use of AI

No use of AI was reported.

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### Author contributions

Conceptualization: NK. Investigation: NK. Resources: AI, MT. Supervision: AI, MT. Visualization: NK. Writing – original draft: NK. Writing – review and editing: AI, MT.

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### Data availability

All of the data that support the findings of this study are available in the main text.

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